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Well-Information Systems as Applied to Geopressured Reservoir Description

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INTRODUCTION

The ultimate objective of most subsurface drilling endeavors is the production of fluids through the well bore. The widespread search for indigenous energy sources has spread to most continental areas of the earth, and even to many offshore provinces. As wells have penetrated deeper into the earth in search of these producible fluids, a wide variety of drilling problems has been encountered. These problems include high temperature and pressure, unstable rock formations, and severe drilling-fluid contamination. To avert the consequences of many of these occurrences, elaborate and sophisticated systems have been developed to monitor the drilling operation and provide sufficient forewarning to ensure operational safety.

In addition to this, however, valuable quantitative information is generated during the monitoring process. This information can be used to describe subsurface structural features, the nature of pore fluids, and certain basic rock properties useful in reservoir engineering. In certain unfortunate instances, this drilling data may be the only reliable source of quantitative well-bore information obtained.

The purpose of this paper is to present a brief discussion of contemporary well-information systems. Equipment and procedures useful for geopressured reservoir description are emphasized.

WELL PREPLANNING

A necessary and important, but sometimes underrated, phase of any drilling operation is well preplanning. Well preplanning can be effectively applied to the simplest or most complex operation.

A preplanning confirmation of abnormal pore pressure in the rocks to be penetrated immediately distinguishes any specific drilling endeavor. This confirmation may be derived from either, or preferably from a combination, of (1) seismic interpretation and (2) offset well information, including subsurface geological correlation, log analysis, mud recap, and detailed drilling records (Houston Geol. Soc., 1971).

In those cases where no abnormal subsurface pressure is indicated, simplified well-monitoring systems are utilized to determine formation tops, provide lithology description, and analyze formation gas. These data are useful for formation evaluation and determination of coring points.

If abnormal pore pressure is anticipated, more elaborate means for monitoring drilling parameters are routinely employed. These well-monitoring systems, in addition to providing subsurface geological information, are used to monitor real-time drilling progress and provide predictions of abnormal pressure while drilling.

WELL- INFORMATION SYSTEMS

The sources of data for well-information systems are real-time operational measurements at the well site and sample analyses of formation cuttings. Basically, two monitoring concepts are employed: measurement and evaluation of certain instantaneous indicators, and graphical and numerical data

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analysis of other indicators for predicting pore pressure increase. For purposes of this discussion, only surface measurements will be considered. It is realized, however, that telemetry from the bit is conceivable, and from research currently underway, a practical system may soon evolve (Business Week, 1975).

Instantaneous Indicators

Instantaneous pressure indicators are those which can be monitored or computed concurrently with the drilling operation. The drilling variables can be grouped as follows: (1) mechanical, (2) hydraulics, (3) mud, (4) bit, and (5) drill cuttings.

Mechanical variables include weight on bit, rotary speed, bit displacement, drilling rate, rotary torque, and hole depth. Hydraulic variables include standpipe and choke pressure, mud-flow rate in/out, and pump-stroke rate. Mud variables are density, temperature in/out, gas content (hydrocarbon and others), rheology, pH, chloride (resistivity), and surface volume. Bit variables include footage and time on bit. Cuttings indicators include density (porosity), composition, and gas content.

TABLE 1
Instantaneous Drilling Indicators

Type of Indicator	Variable	Purpose of Management
Mechanical	Weight on bit	Sudden increase in BHP, drilling equations, bit-wear studies
	Rotary speed	Rotary horsepower, drilling equations
	Bit displacement	Compute drilling rate
	Rotary torque	Rotary horsepower, bit-wear studies
	Hole depth	Depth correlation
	Drilling rate	Sudden increase in EHP, drilling equations, lithology
Hydraulic	Standpipe pressure	Washout detection, hydraulic analysis, sudden increase in BHP
	Choke pressure	Pressure control
	Flow rate	Pressure detection, lost-return analysis, sample lag
Mud	Stroke rate	Pump efficiency
	Density	Pressure detection and control
	Temperature	Pressure detection
	Gas (hydrocarbon and others)	Pressure detection, formation evaluation
	Rheology	Hydraulic control, hole cleaning, mud treatment
	pH	Mud control, corrosion
Bit	Chloride (resistivity)	Pressure detection
	Surface volume	Pressure detection, mud treatment
	Footage	Well correlation, wear studies
	Time on bit	Wear studies, drilling rate
Cuttings	Density (porosity)	Pressure prediction, lithology change
	Gas content	Formation evaluation, pressure indication

It should be pointed out that certain of these instantaneous indicators are in fact lagged in real time by travel up the annulus. These lagged parameters include mud gas and drill cuttings. This lag time, however, rarely exceeds a few hours at most.

The instantaneous indicators are useful in supplying information upon which operational decisions are made. With relatively simple mathematical manipulation, they form the basis for calculating other important drilling criteria. For example, the mechanical and bit indicators can be combined to predict bearing and tooth wear. Mud and hydraulic parameters are used to compute bit hydraulic horsepower, annular velocity, and pressure drop in the circulating system.

These indicators, variables and uses of variables are summarized in table 1.

Predictive Indicators

The predictive, or leading, indicators are those that can, when graphed as a function of depth, be interpreted to predict increasing pore pressure. The leading indicators include (1) normalized drillability, (2) bottom-hole temperature, (3) shale density, (4) shale factor (clay content of shale), and (5) connection and trip gas.

Normalized drillability can be computed from simplified drilling rate equations, (Jordan and Shirley, 1966) or inferred from more complex regression analyses of drilling variables (Bourgoyne and Young, 1974). Bottom-hole temperature gradients are computed from surface mud-temperature measurements and well-bore heat-flow characteristics. Shale properties are determined by simple laboratory analyses at the well site. Connection and trip gas are observed after longitudinal pipe movement, and are a direct result of reduced hydrostatic pressure.

These indicators are usually plotted on a 1-inch- or 2-inch-per-1,000-feet trend log, and when collectively analyzed, provide an indication of pore pressure changes. In practice, the differential pressure between static (or circulating) pore pressure and rock pore pressure can be estimated to an accuracy of 0.1 ppg., or approximately 50 psi at 10,000 feet.

Estimation of pore-pressure magnitude and prediction of changing pressure with depth provides a basis for selecting mud weight for pressure control and mud chemistry for borehole stability.

DATA INTERPRETATION

Success or failure of the drilling operation depends upon well-bore control—control of pressure, formation instability, and mud chemistry. Proper interpretation of drilling information is essential to maintenance of well-bore control. Thus, the key to safe and economical drilling operations is accurate analysis and interpretation of drilling information. Various interpretation procedures are useful in drilling geopressured reservoirs.

Lithology

Lithology, or the gross physical character of rock, is basic to data interpretation because the criteria for interpreting abnormal pressure development can be quite different in dissimilar lithologies. A pore-pressure transition from normal to abnormal may occur gradually in a sand-shale sequence. Such sequences are developed from relatively young sediments and the cause of pressure is rapid deposition and a relatively thick shale section. Occurrence of abnormal pressure in carbonate facies, however, is generally considered to be a secondary phenomena, and the transition can be very abrupt, often occurring over an interval of a few feet.

The classical pressure indicators—drillability, shale density (porosity), shale factor, and temperature increase—were studied first in the abnormally pressured areas of the U.S. Gulf Coast, where the problem of high pressure constituted a significant drilling hazard.

Utilization of these indicators in carbonate, or hard-rock facies is less well established. In carbonate interpretation, drilling equations, mud temperature changes, and chloride changes provide the best information. In some cases, the shale-factor parameter has accurately reflected a pore-pressure change. Carbonate pressure predictions are most effectively confirmed by sonic-log evaluation. Knowledge of rock lithology is most important in abnormal-pressure interpretation.

Gas Analysis

Sensitive hot-wire gas analyzers are used to monitor the gas content of drilling mud. They provide only a relative indication of gas content, however, and quantitative analysis must be performed by chromatography. Three gas measurements are important: background gas, connection gas, and trip gas. Cuttings gas is usually introduced into the drilling mud by bit cuttings and is rapidly dissipated during one circulation. Background gas is introduced to the borehole by a pressure imbalance, and it can be reduced by increasing the mud weight. An increasing or decreasing trend with time is important. Often, background gas increases prior to drilling into the first permeable, porous, abnormally pressured zone. Connection and trip gas are introduced into the mud system by pipe movement, which causes reduced bottom-hole pressure. This gas is circulated to the surface, where large but temporary increases in mud gas are observed. Trip and connection gas should be corrected for background content prior to interpretation.

Increases in surface gas following circulation of drilling breaks (an indication of porosity), are further analyzed by means of chromatography. Samples of mud are subjected into the chromatograph. Precise determination of gas composition after absorbing inerts and water vapor can be used in a ratio technique (Pixler, 1968) to predict the possible productivity of the formation penetrated. Presence of heavier paraffin-series gas components normally indicates commercial productivity if the concentrations of the hydrocarbons are

$$C_1 > C_2 > C_3 > C_4 > C_5 + \dots \quad (1)$$

Rock Properties

Rock properties are directly measured by cuttings analysis and inference from drilling equations. Measured properties include density (porosity) and chemical composition. These properties are most important in shales. Shale density is measured by either the mud-balance method or variable-density column. Samples gathered at one interval are usually measured and then averaged prior to recording. Plots of shale density with depth indicate an exponential compaction trend.

$$\rho = \rho_0 e^{CD} \quad (2)$$

Where

- ρ = shale density,
- ρ_0 = shale density at reference depth,
- C = constant,
- D = hole depth.

Deviations from this trend are interpreted as abnormal-pressure development. If shale density decreases with increasing depth, the effective stress on the rock matrix is assumed to be decreasing, and therefore pore pressure is increasing, since the total overburden is known.

$$S = \sigma + P, \quad (3)$$

where

S = overburden stress (≈ 1 psi per foot)

σ = effective stress

P = pore pressure

On a regional basis, the magnitude of overpressure can be estimated by departure curves.

Diagenesis, or postdepositional alteration, of shales occurs with burial at a temperature of about 221°F. The clay transformation from montmorillonite to illite results in the liberation of free water in an amount equal to more than half the volume of montmorillonite altered (Burst, 1969). With increasing depth, the percentage of illite in shale gradually increases. A reversal in this trend, caused by incomplete clay transformation, is indicative of a pressure transition. The shale factor, of montmorillonite content of a shale sample, may be determined by a simple titration test with methylene blue (Gill and Weintritt, 1971).

Temperature

The presence of excess free water in clay sediments in and overlying abnormally preserved zones alters the thermal conductivity of the porous rock system. As heat flows from the earth's core, zones of low thermal conductivity (excess water) increase the geothermal gradient. For this reason, increases in flow-line temperature are often an indication of increasing pressure. The temperature distribution in a circulating system is strongly dependent on many variables, however, and temperature data must be carefully interpreted. Numerous mathematical models describing this problem have been published (Holmes and Swift, 1970). These models can be used with surface measurements to predict formation-temperature gradient.

Drilling Models

Drilling rate in rock formations of known strength can be predicted by means of simplified drilling models, such as

$$R = R'(W, N, B, K, \Delta P), \quad (4)$$

where:

R = drilling rate,

W = bit weight,

N = rotary speed,

B = bit condition,

K = rock strength,

ΔP = pressure differential.

Differential pressure, P , is a function of mud pressure and pore pressure:

$$\Delta P = P_m - P_f, \quad (5)$$

where

P_m = mud pressure,

P_f = pore pressure.

Mud pressure is the combined pressure due to hydrostatic pressure, annular-pressure losses, bit-nozzle pressure, and fluidic inertial forces due to

rotation. By computing mud pressure and using a model of drilling performance in homogeneous formations, pore pressure can be estimated. Note that several of the independent variables in equation 4 were mentioned previously as instantaneous indicators.

Pore Pressure

The present state of well monitoring technology precludes direct and precise measurement of rock pore pressure. However, by careful analysis of drilling indicators, estimates to within 0.1 ppg at 10,000 feet can be consistently predicted in sand-shale lithologies.

A tabulation of drilling parameters useful for pore-pressure prediction are shown in table 2, together with the positive response criteria. This table does not include the obvious instantaneous indicators, such as drilling breaks, pit-level increases, mud flow and pump pressure.

TABLE 2
Drilling Parameters for Pore-Pressure Prediction

Parameter	Abnormal Pressure Response or Use
Drilling rate	Increasing with depth, use for correcting lithology and bit-drilling trend.
Drilling equation	Decreasing with depth, use for normalizing effects of operating variables
Background gas	Gradual increase
Connection gas	Increase
Trip gas	Increase
Shale density	Decrease
Shale factor	Increase
Chloride	Gradual increase as pore pressure increases, may decrease in top of formation
Temperatures	Increasing flow-line temperature and bottom-hole gradient

Computer Applications

As drilling technology has evolved, the number and frequency of measurements required for well monitoring, reservoir description, and pressure prediction has increased. In offshore environments, vessel position, weather monitoring, and other special requirements have compounded this data-flow problem. Modern digital computers, aided by reduction in price and increases in reliability, are ideally suited for handling the processing of well information. Well-site computers are now used for well-monitoring data collection, on-line analysis, off-line analysis, weather monitoring, vessel monitoring, data storage, closed-loop circuitry, alarm, and data transmission.

The use of computer equipment at the well site is expected to increase as drilling costs escalate, particularly in remote or marine locations.

Limitations of Data Interpretation

As with any complex process, certain limitations are inherent in the interpretation of well data.

Cuttings analysis. Hole sloughing may generate formation chips. A major problem is obtaining a representative bottom-hole sample. Also, complex subsurface geology may complicate the development of meaningful trends.

Drilling equations. Rock drilling strength, or drillability, is undefined. In the development of empirical drilling equations, the constant that is introduced may disguise important variables that are not specifically expressed. This drilling strength parameter may contain responses that are due to compressive strength, hole cleaning, porosity, and many other physical rock constants. This fact complicates interpretation in rapidly changing lithology.

Mud temperature. Many ill-defined parameters are introduced, not the least of which is introduction of material in the mud and the dissipation of bit energy. Several hours of circulation at constant flow rate may be required for flow-line temperature stabilization.

Sample Logs

Examples of data presentation are shown in figures 1 through 4. Figure 1 shows a mud log; figure 2, a show evaluation; figure 3, a drilling parameter log; and figure 4, a computerized log.

Equipment

Equipment for distilling gas from a mud sample, and a chromatograph for gas analysis are shown in figure 5.

An interior view of a mobile, computerized well information system logging unit is shown in figure 6.

SUMMARY

Efficient execution of a proposed drilling operation begins with preplanning. The well information systems to be employed depend upon the cost and complexity of the operation. If abnormal pressures are anticipated, equipment and techniques have been developed for monitoring instantaneous indicators and drilling trends.

The occurrence of pressure can be detected with sufficient accuracy to ensure safe and economical operation.

Reservoir data accumulated during the drilling operation can be beneficial to both drilling and reservoir engineers. These data can be made available in the form of tables and logs. Computer-generated data can be stored for later processing.

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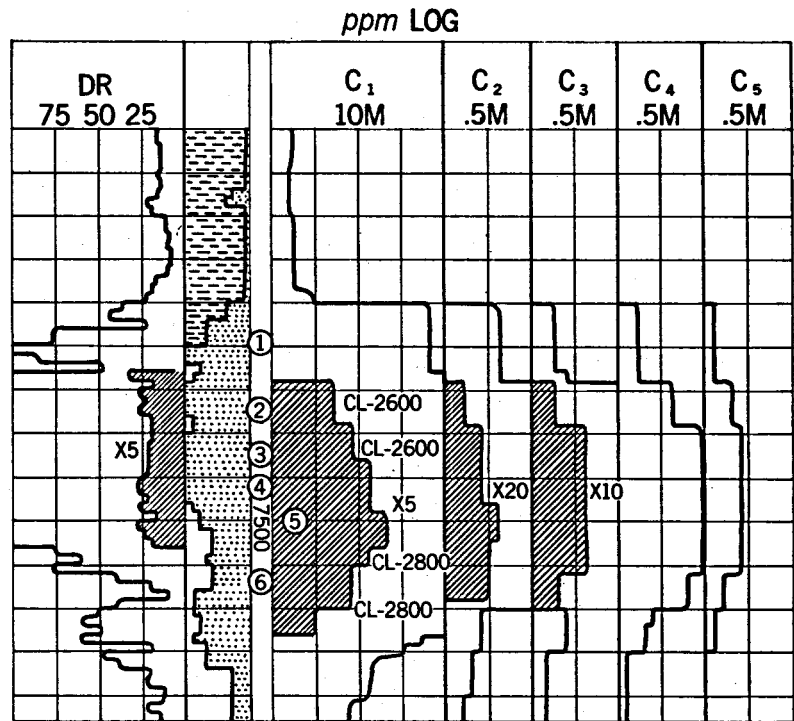


Figure 1. Mud Log (Pixler, 1968).

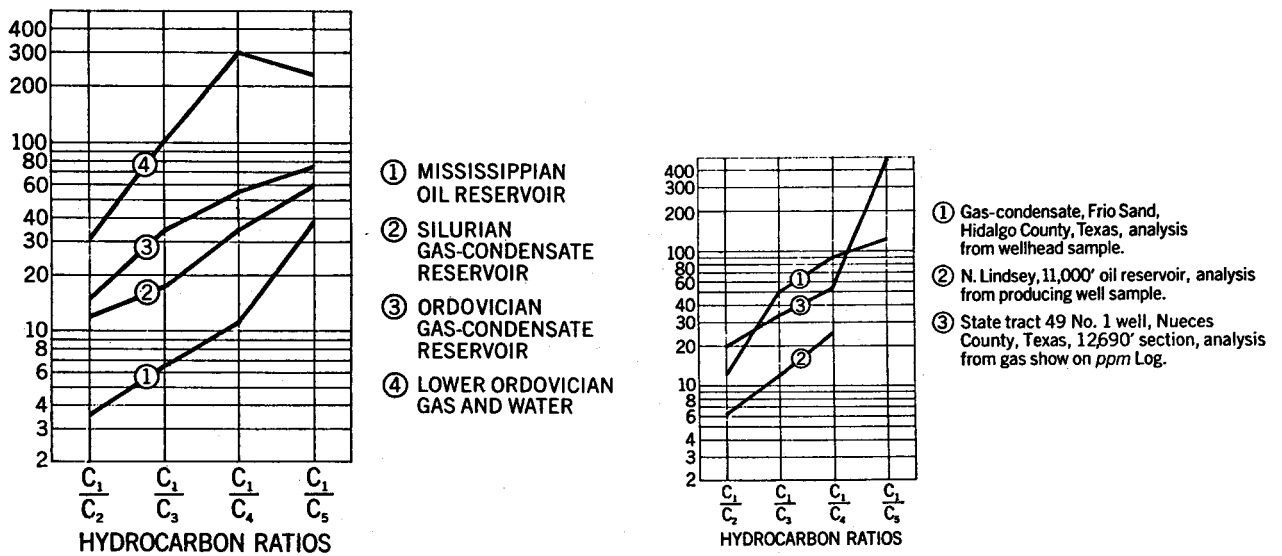


Figure 2. Show Evaluation (Pixler, 1968).

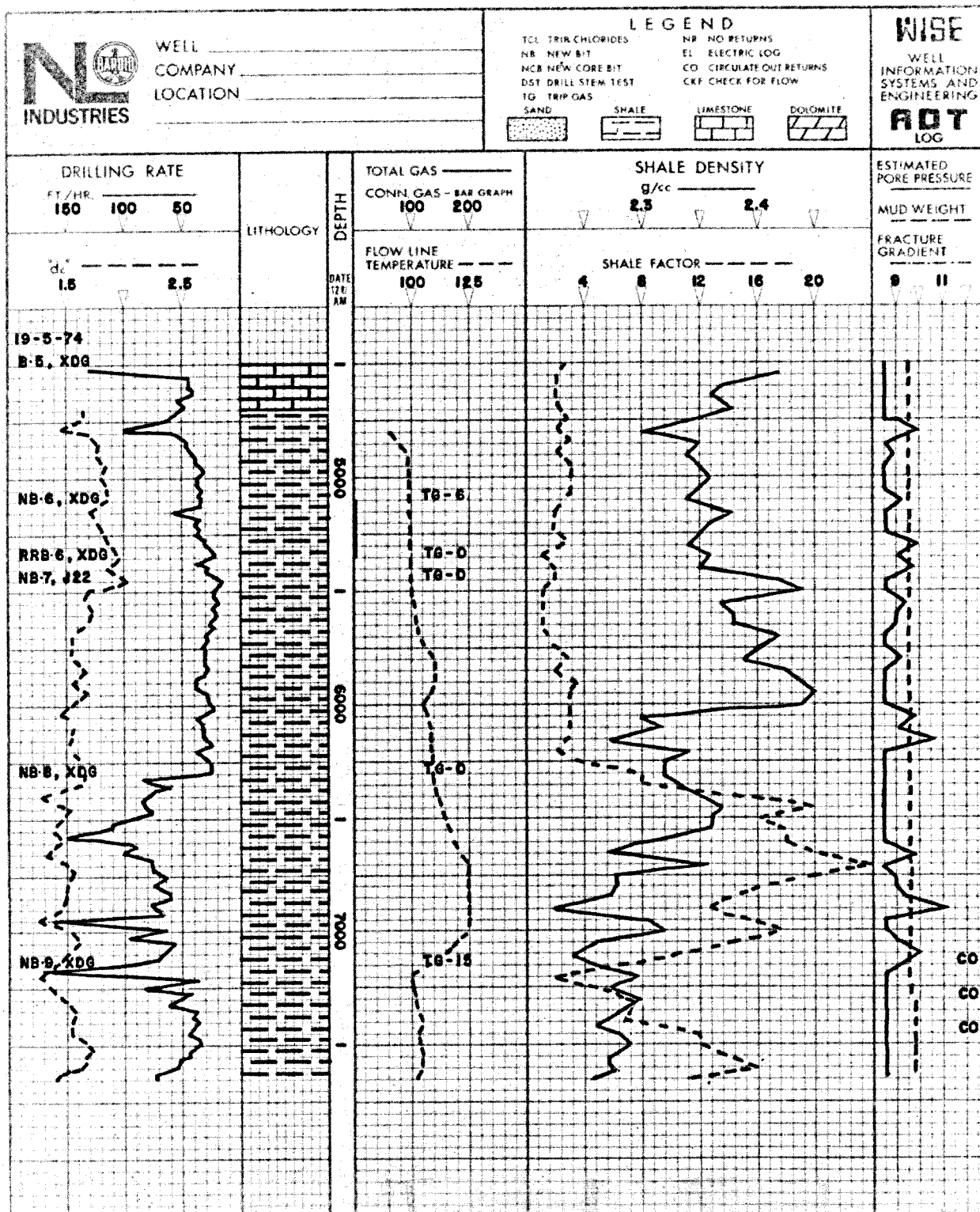


Figure 3. Drilling-Parameters Log.

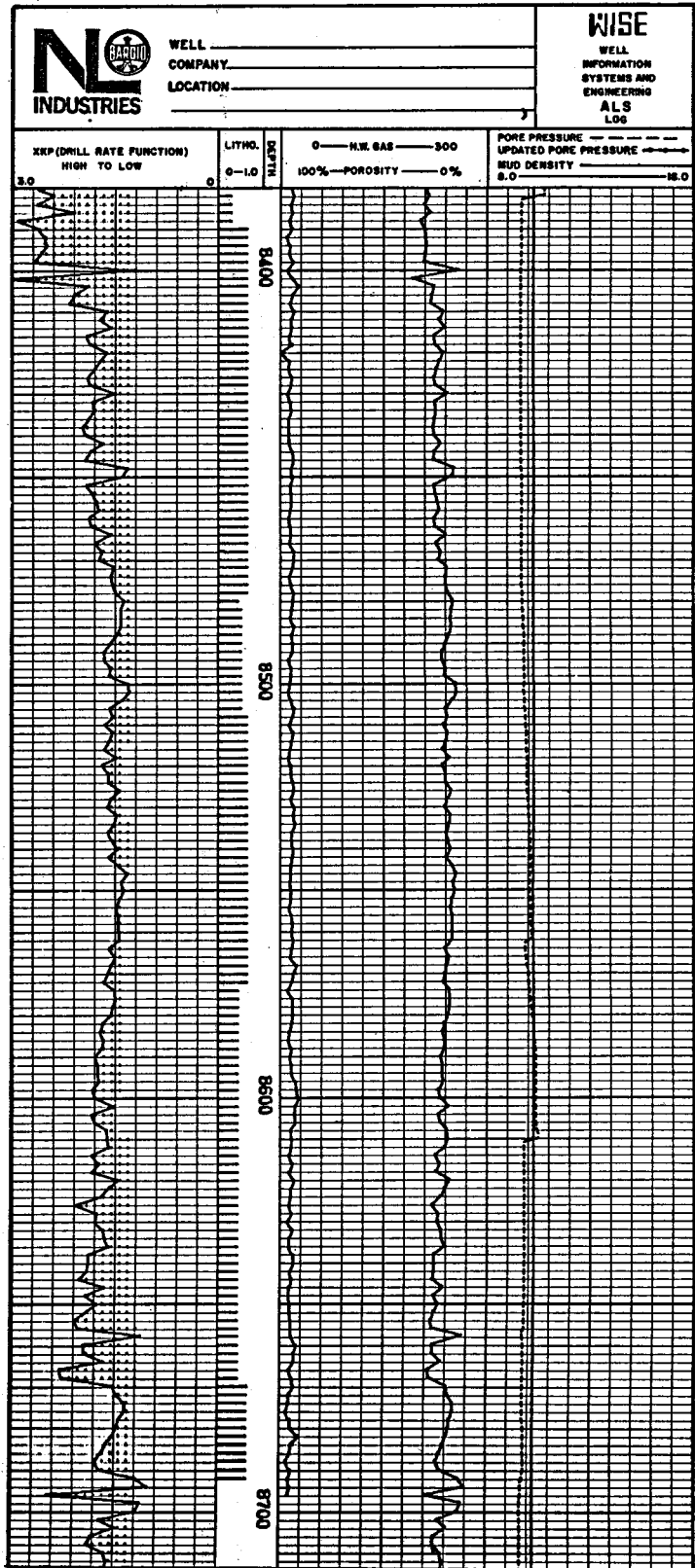


Figure 4. Computerized Log.

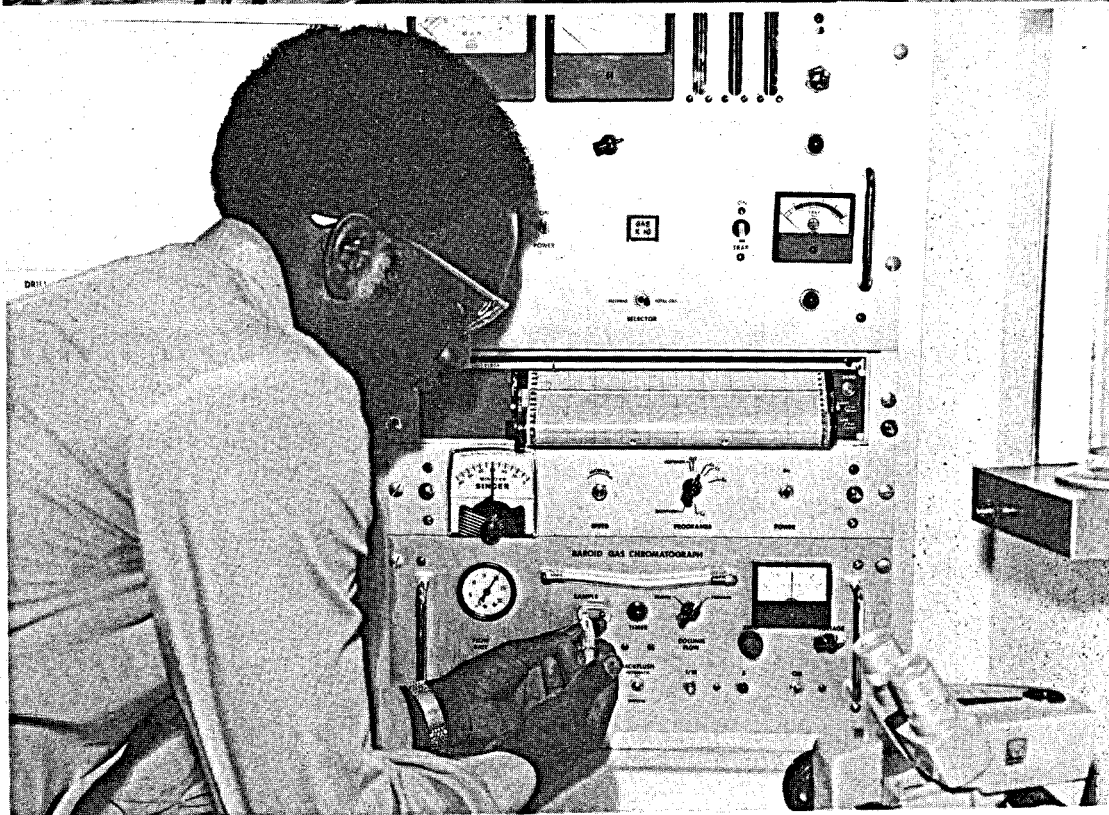
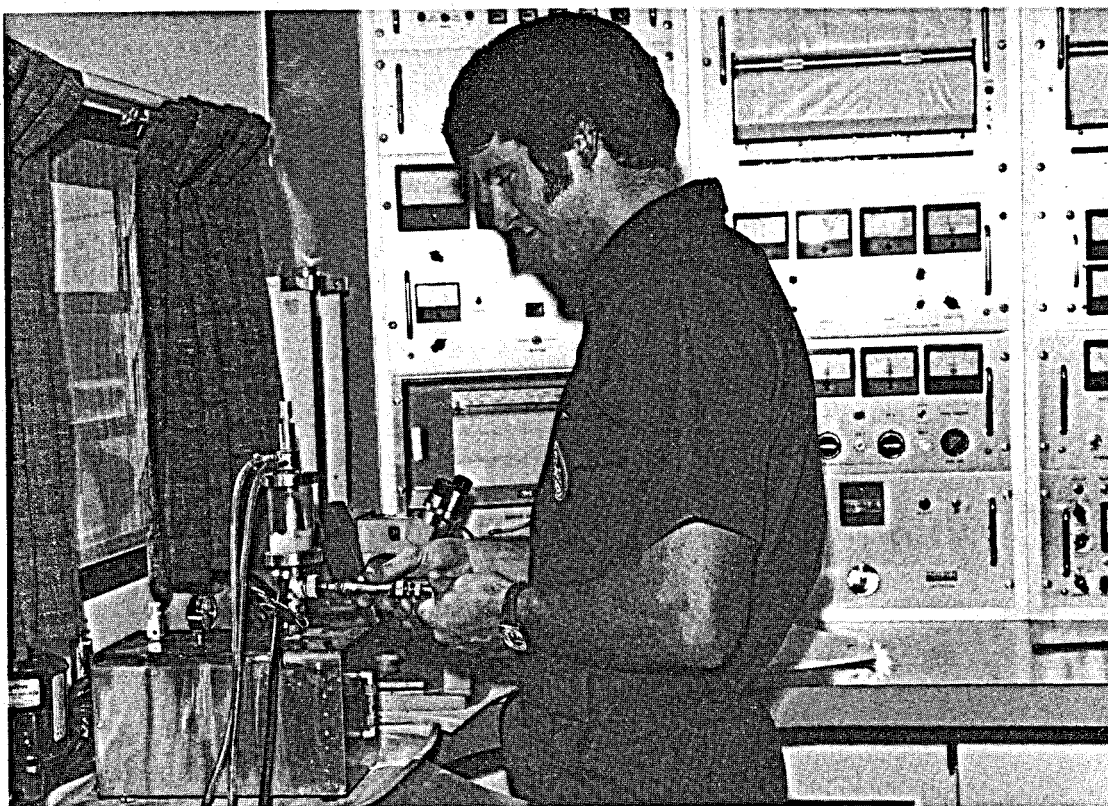


Figure 5. Steam still and gas chromatograph.

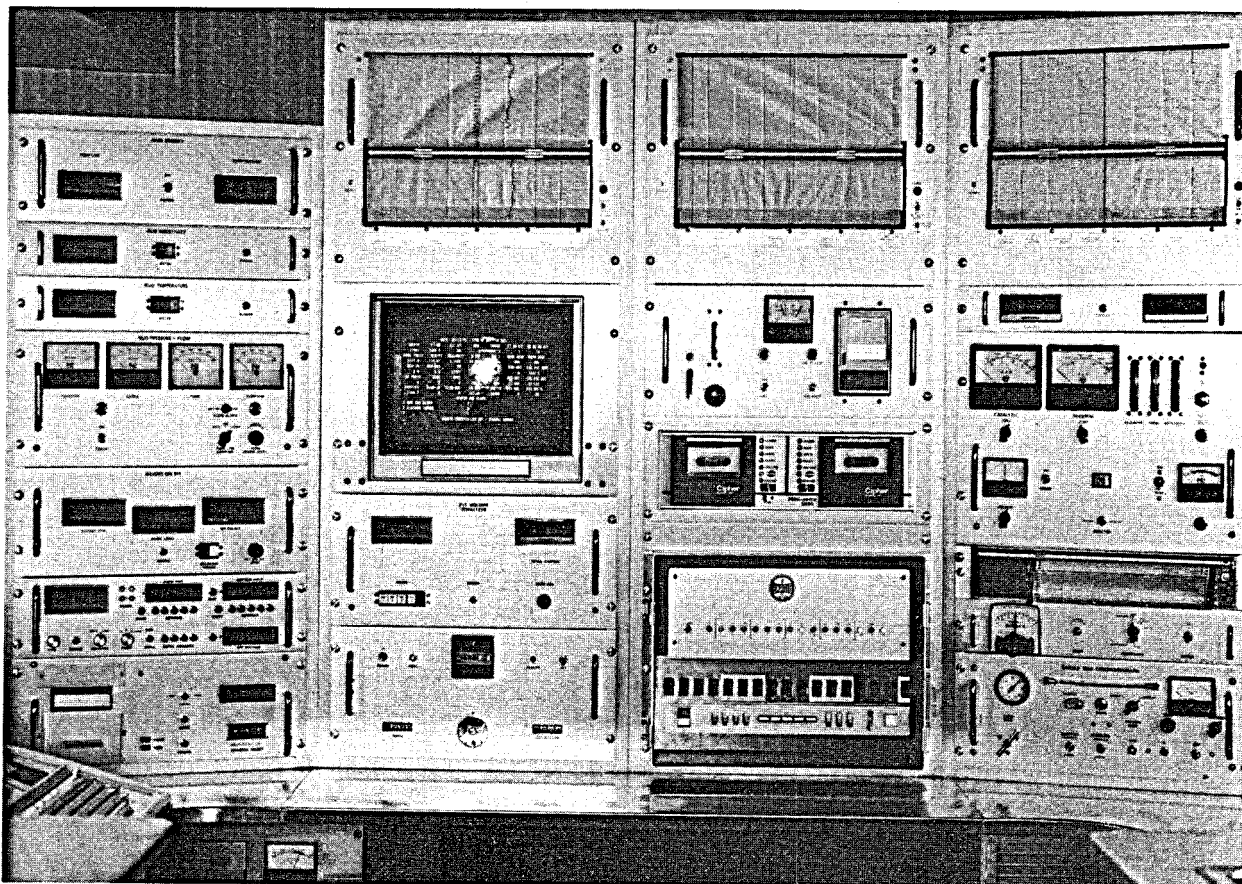


Figure 6. Computerized logging unit.

Discussion

Podio

Thank you, Dr. Young. We have time for about two questions.

Hise

Louisiana State University

I was trying to put something you said together with something that was said yesterday. Did you say that as you enter abnormal-pressure shale, your sodium montmorillonite seems to increase? Is that what your methylene-blue tests are telling?

Young

Yes.

Hise

One of the mechanisms yesterday was the conversion of montmorillonite to illite, which would seem just the opposite.

Young

Not exactly. What's going on here, I think, the way I read the literature, is that this diagenesis takes place at about 200°—something like that. And that diagenetic process generates almost half the pore volume of water that you have in the bulk sample before. What we're trying to measure is the retardation of the diagenesis as you're going into abnormal pressure. This is very fine measurement. It's pretty precise, but it's basically a measurement of the increase in sodium content with depth, which is an anomaly. You don't expect to see that in a normally compacting cross-section of sediments.

You have this diagenesis taking place and as you go deeper, you would expect to have less and less sodium clay. The fact that this pore water is trapped and it can't get out retards the diagenesis and gives rise to more sodium clay than you might anticipate at that depth. I think that's what we're saying.

Podio

Are there any other questions?

Barnea

Can you detect gases other than hydrocarbon in the mud?

Young

Yes, we have instrumentation for CO₂, H₂S₂ (the two predominant types), and we can change the range from 0 to 5 parts per million.